

AN EDDY CURRENT SENSOR FOR THE MEASUREMENT OF RESISTIVITY AND TEMPERATURE OF ALUMINUM ROD DURING EXTRUSION PROCESSING

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INTRODUCTION

Optimization of the speed of production and the control of quality of extruded aluminum products requires the measurement of the temperature of the extruded product during processing. This temperature measurement should be by a non-contact sensor placed as close as possible to the extrusion die, and the measurement should be accomplished and reported with sufficient rapidity to be used in a feedback control loop. For this purpose, an eddy current sensor which performs an on-line measurement of resistivity and converts the measurement to the corresponding temperature has been developed. This project is being conducted jointly by The Aluminum Association and the National Bureau of Standards.

A schematic diagram illustrating how the sensor would be integrated into an automated control system for regulating extrusion processing is shown in Fig. 1. The temperature of the extruded product depends on the initial temperature of the input billet and the speed of extrusion, which is determined by the hydraulic ram pressure. Friction in the die generates heat which can damage the product if excessive. On-line feedback is to be used to regulate extrusion speed. The temperature measurement also would be used to control the furnace which prepares the billets for extrusion. In this report, results are presented on laboratory tests and a plant demonstration of temperature measurements on solid round, solid square, and hollow square extrusion shapes.

DESIGN OF THE SENSOR

To perform the measurement of resistivity, a two-coil system based on a commercially available Impedance/Gain-Phase Analyzer was used. The coil assembly is shown in Fig. 2. The primary, seen on the outside, is cooled by compressed air when in plant use. The secondary is concentric with the primary, and is cooled by circulating water. The interior is protected by a tube of electrically insulating boron nitride which provides lubricity for the passing product.

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ALUMINUM EXTRUSION TEMPERATURE SENSOR

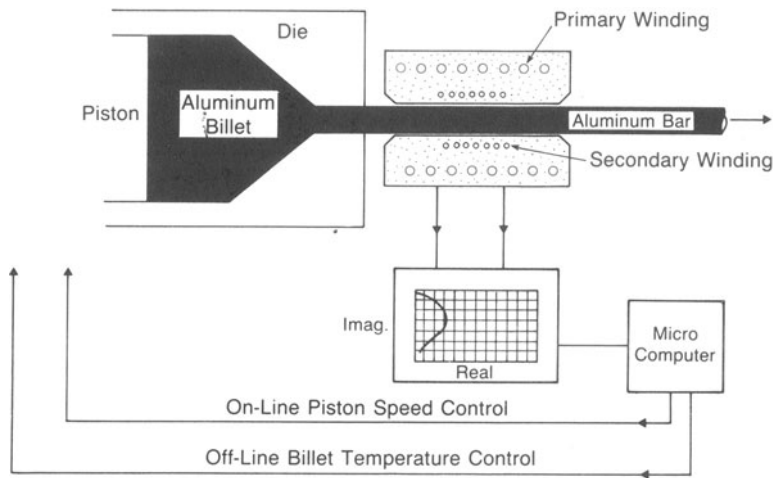


Fig. 1. Schematic diagram of the integration of an eddy current temperature sensor into an extrusion processing control system.



Fig. 2. Coil assembly mounted in canister. During processing the extruded products pass through the four graphite lined channels; the sensor resides in one of the channels.

The circuit is shown in Fig. 3. The primary solenoid, driven by the analyzer's oscillator through an audio power amplifier, impresses a uniform AC magnetic field on the test material. The voltage across the resistor in the primary circuit is proportional to the primary current and gives a measure of the AC field on the sample; this is detected in the reference channel of the analyzer. The emf induced in the secondary coil depends on the resistivity of the test material; this is measured in the test channel of the analyzer. The analyzer is programmed to report the ratio of the secondary emf to the primary current and the relative phase of these quantities at each frequency of interest. From these measurements taken on the empty coil system and again with the test material present, the normalized impedance curves can be obtained in the conventional form [1] also given by Libby [2].

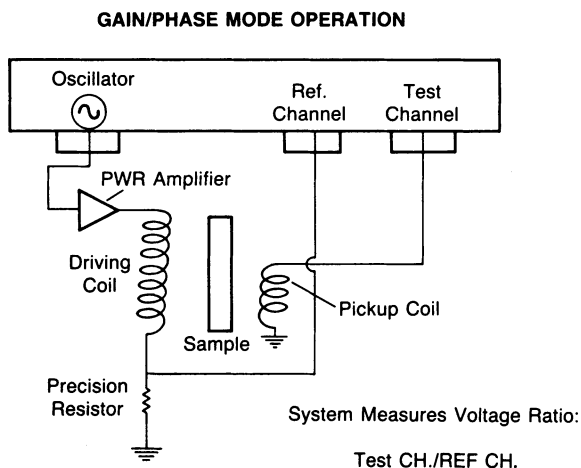


Fig. 3. Circuit diagram of the two-coil impedance measurement system. The coils and test sample are concentric, with the primary outermost and the shorter secondary centered just inside the primary.

This approach has three principal advantages over a single coil design:

- 1.) The determination of resistivity from a transfer impedance allows a power amplifier to be used to enhance signal strength at low frequencies, while using available equipment.
- 2.) The field impressed on the test material is very uniform over the region being sampled by the shorter secondary test winding. This allows a simple analysis which does not need to take into account end effects related to fringing fields, as would be the case in a single coil system.

3.) The system is insensitive to temperature variation in the coils. The output signal from the secondary is directed to a high impedance input of the analyzer; hence the variation of the coil resistance with temperature does not influence the measurement. Variation of the primary coil resistance is insignificant because the primary current, and thus the exciting field, is measured directly via the primary circuit resistor.

Defining gain in this context as the ratio of secondary emf to primary voltage drop across the primary standard resistor, and ϕ as the corresponding phase difference, we obtain the normalized impedance at each frequency by the relation:

$$Z_N = (\text{gain}/\text{gain}_0) j \exp(-j(\phi - \phi_0)) \quad (1)$$

where zero subscripts on the right represent empty coil values, and unsubscripted terms refer to values with the test sample present. In Fig. 4 we show several normalized impedance curves measured on a series of aluminum rods of varying diameters.

The resistivity is obtained by the following procedure. From measurement of the impedance at one frequency we may determine the angle α , as shown in Fig. 3. When angle α is known, the quantity

$$x = R/(\sigma\omega\mu_0) \quad (2)$$

is determined uniquely. In Eq. (1) σ is the conductivity, ω the angular frequency, μ_0 the permeability, and R the radius. All impedance curves of uniform cylinders with the same value of α have the same value of x . We have prepared a computer lookup table for determining x from α . The most precise measurement of conductivity is obtained when the frequency is selected so that the impedance value lies near the knee of the curve.

For extrusions of other cross-sectional shapes, the impedance curves must be calculated specially. We have used previous work [3] to calculate the relation of angle α to $x = a/(\sigma\omega\mu_0)$, where a is now the edge of the square cross section. Another lookup table was prepared for this purpose.

The variation of resistivity with temperature for alloys 6061 and 6063 was obtained in the laboratory. Drilled aluminum rods in which thermocouples were placed were heated and placed in the sensor. Resistivity vs. temperature curves were recorded during cooling. Data from these runs were averaged to determine a resistivity vs. temperature lookup table. The use of lookup tables was preferred to evaluation of analytic formulas because of its greater speed. In measurements performed in the laboratory, the computed temperature obtained by the sensor and the values measured by a thermocouple at the center of the solid sample agreed within ± 10 deg F during cooling from 1100 deg F to 950 deg F. Each temperature measurement requires 1.2 sec. In future designs this time could be reduced.

In addition to the temperature measurement, it is also possible to use the high frequency limit of the impedance curve to obtain the fill-factor of the sample with respect to the secondary coil. This yields the cross-sectional area of the sample, or the equivalent diameter in the case of a cylindrical rod. In laboratory tests, the diameter measurements were accurate to ± 0.001 in for rods ranging from 0.75 in to 1.375 in. The diameter measurement takes three seconds to be performed. The greater time is needed because the measurement requires impedances at five frequencies and a least squares extrapolation of the curve to the imaginary axis.

PLANT TRIALS

The sensor system described above was installed for testing at the Cressona Aluminum Co., Cressona, PA. The coil system was placed in one channel of a four channel canister, as shown in Fig. 4. During extrusion, the cannister is mounted close to the die with the sensor within one foot of the die. Four aluminum shapes pass through graphite guides; one of the channels houses the sensor. Extrusion speeds were approximately 70 ft/min, but this varied because of billet temperature inhomogeneity; it also was varied for experimental purposes.

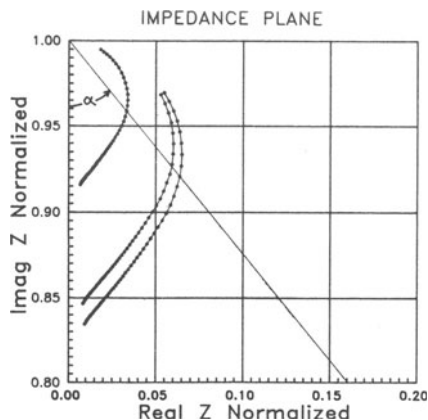


Fig. 4. Impedance curves of three aluminum rods of varied diameters, measured under laboratory conditions. Angle α is a parameter used in computing the value of $x=R/(\sigma\omega\mu_0)$ for any point on the curves.

Fig. 5 shows a typical temperature measurement sequence for extrusion of round rod. Initially the colder front part of the billet was extruded; also the die was cool. This produced a slow extrusion rate. As the die heats from friction, and as the hotter part of the billet reaches the die, the extrusion speed increases and less ram pressure was needed. Typically the temperature rose to a plateau as the operator adjusts ram pressure to hold a constant extrusion speed. After 70 sec, see Fig. 5, the billet was exhausted, extrusion stopped, and the product was severed from the die. The sensor then monitored the cooling of the stationary material in the coil.

The same extrusion press, canister, and sensor arrangement was used for temperature measurements on solid square aluminum stock, as shown in Fig. 6. The behavior was similar to the previous case. In this case the appropriate impedance curves for square sample cross-section was used to interpret the measurements. In this run the speed was intentionally varied to demonstrate heating effects.

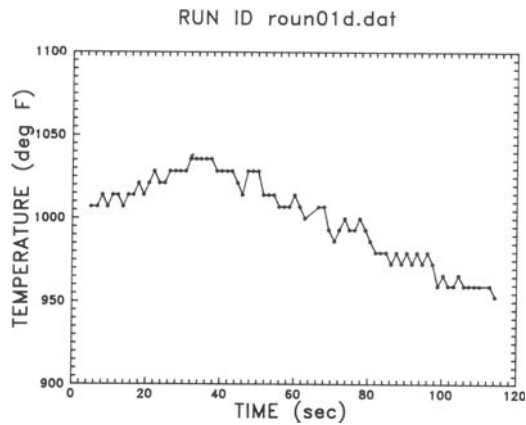


Fig. 5. Measured temperature as a function of time for 6061 aluminum 1" round rod during extrusion.

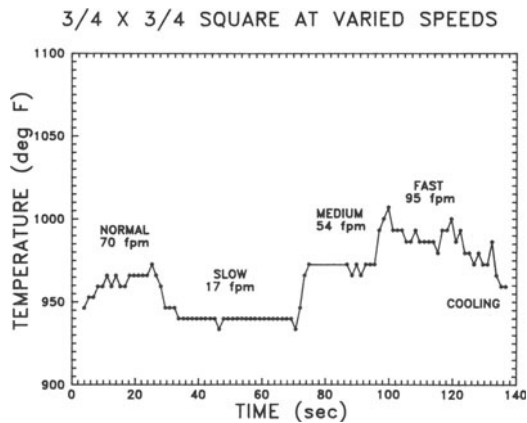


Fig. 6. Measured temperature as a function of time for 6061 aluminum 3/4" square stock during extrusion. The speed was intentionally varied to demonstrate heating effects.

Square hollow tubing was also examined, but in an extrusion press of the type which does not have a removable cannister. The coil system was placed about three feet from the die on the flat bed which received the product.

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